50,000 Laps Around Mars: Navigating the Mars Reconnaissance Orbiter Through the Extended Missions (January 2009 – March 2017)

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Orbiting Mars since March 2006, the Mars Reconnaissance Orbiter (MRO) spacecraft continues to perform valuable science observations, provide telecommunication relay for surface assets, and characterize landing sites for future missions. Previous papers reported on the navigation of MRO from interplanetary cruise through the end of the Primary Science Phase (PSP) in December 2008 and on maneuvers performed through November 2016. This paper highlights the navigation of MRO from January 2009 through its 50,000th orbit around Mars on March 27, 2017, an eight-year period covering the Extended Science Phase, the first three extended missions, and a portion of the fourth extended mission which began on October 1, 2016. Since the beginning of the PSP in November 2006, MRO's navigation performance has continued to exceed expectations. Over that period of time, the mission has returned over 300 terabytes of data.

1. Introduction

Launched from Cape Canaveral Air Force Station on August 12, 2005 and after an interplanetary cruise of seven months, the Mars Reconnaissance Orbiter (MRO) spacecraft entered orbit around Mars on March 10, 2006. After five months of aerobraking and three months of transition to the Primary Science Orbit (PSO), MRO began science operations in November 2006. Over ten years later, MRO continues to perform valuable science observations at Mars, provide telecommunication relay for surface assets, and characterize landing sites for future missions. MRO reached an important milestone completing 50,000 orbits around Mars on March 27, 2017. Previous papers reported on the navigation of MRO from Mars Orbit Insertion (MOI) through the end of the Primary Science Phase (PSP) in December 2008.[1,2] This paper will highlight the navigation of MRO through the extended missions from January 2009 through March 2017, specifically the Extended Science Phase and four extended missions. The MRO Navigation Team has been providing mission support through these mission phases by performing the spacecraft orbit determination (OD) and maintaining the PSO through propulsive maintenance maneuvers (see Reference 3). This manuscript will also describe the driving performance requirements levied on the Navigation Team and how well those requirements have been met during the extended missions.

2. Mission Overview

MRO has completed several missions at Mars: the Primary Science Phase (PSP), the Extended Science Phase (ESP), and three extended missions (EM1, EM2, and EM3). MRO is currently in its fourth extended mission (EM4) which began on October 1, 2016 and scheduled to end in September 2018. As an asset of the Mars Exploration Program Office, MRO continues to perform science observations and has provided telecommunication relay support to the Mars Exploration Rover (January 2004 – present), the Mars Phoenix lander (May 2008), and Mars Science Laboratory (August 2012 – present).[4] It has also observed the close flyby of Comet Siding Spring at Mars in October 2014[5] and imaged the ExoMars lander Schiaparelli in October 2016.[6,7] MRO plans to provide telecommunication support for the Entry, Descent, and Landing (EDL) phase of the InSight mission (NASA) in November 2018. Since the beginning of the PSP in November 2006, MRO's navigation performance has continued to exceed expectations. MRO requires a tight orbital accuracy for operation of its high-resolution camera HiRISE; this is made more challenging given the variability of the Martian atmosphere.

2.1. MRO Spacecraft

The spacecraft axes, as shown in Figure 1, are defined such that Z is positive along the nadir deck where the majority of the science instruments are located. The six engines for MOI and the six Trajectory Correction Maneuver (TCM) thrusters are located along the +Y axis. The large solar panels are on
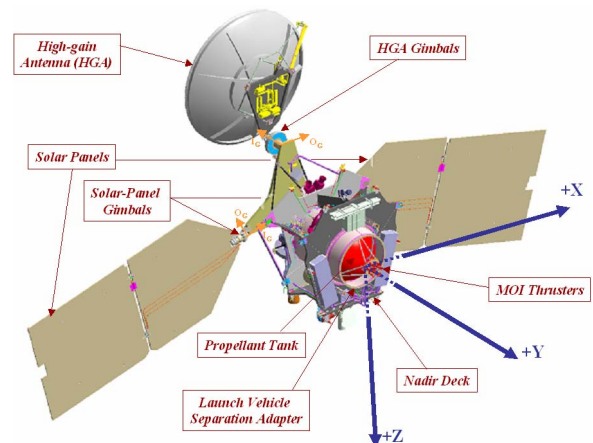

Fig. 1. Diagram of the MRO spacecraft.

the ±X axes, canted 15 deg towards +Z. The 3-meter diameter High Gain Antenna (HGA) is located opposite the nadir deck. During science operations, the nadir deck is configured towards Mars, while the X-axis is directed along the velocity vector. Both solar panels and HGA will swivel to track the Sun and Earth, respectively. MRO is gravity-gradient stabilized to sustain the nadir-to-planet orientation. Spacecraft attitude is maintained by the Reaction Wheel Assembly (RWA); this consists of three 100 Nms wheels mounted perpendicular to each other, augmented by a fourth redundant wheel in a skewed orientation.[8] The monopropellant propulsion subsystem uses three sets of thrusters; the aforementioned MOI and TCM thrusters, and the Attitude Control System (ACS) thrusters. The TCM thrusters have been used for Orbit Trim Maneuvers (OTMs) since February 2007. The ACS system uses balanced thrusters: thruster pairs are fired together, and are arranged so that this imparts a net zero ΔV. The spacecraft bus built by Lockheed Martin provides a stable platform for the payload suite of science instruments. These instruments, mounted for observation on the +Z axis of the spacecraft (nadir deck), are used to perform remote sensing of the Martian atmosphere as well as surface and subsurface conditions. They include the High Resolution Imaging Science Experiment (HiRISE) camera, the CRISM Imaging spectrometer, the Mars Climate Sounder (MCS), the Mars Color Imager, the Context Camera (CTX), the Shallow Subsurface Radar, and the Electra engineering payload. Among MRO's instruments, high fidelity imagery is performed using the HiRISE camera. This key resource is able to supply imaging of orbiting or landed assets on Mars as well as mission support observations of possible future landing site locations. Relay telecommunication support in the UHF frequency range is provided by the Electra Proximity Link Payload.

2.2. MRO Primary Science Orbit

The Primary Science Orbit (PSO) for MRO operations is a 252 km × 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM ± 15 minutes. The mean orbital elements for the 50,000th orbit are shown in Table 1. The orbit is designed to exactly repeat after 4602 revolutions in 349 sols with separation between ground tracks of less than 5 km at the equator. The near-repeat cycle used for science planning is a 211-orbit cycle (16 sols) that walks about 0.5 deg (32.5 km) in longitude westward from the previous cycle. The orbit maintenance is done based on this near repeat cycle via propulsive maneuvers.

Table 1. MRO mean orbital elements on March 27, 2017, 50,000th orbit.

Periapsis Epoch: 27-Mar-2017 11:57:51.031 ET	
Semi-Major Axis (a)	3649.2801 km
Eccentricity (e)	0.0057
Inclination (i)	92.5787°
Argument of Periapsis (ω)	269.06956°
Right Ascension of Node (Ω)	235.7435°
True Anomaly (v)	0.0°
Additional Orbit Information	
Descending Equator Epoch (Start of 50,000th Orbit): 27-Mar-2017 11:30:23.949 ET	
Apoapsis Epoch: 27-Mar-2017 12:53:43.282 ET	
Period (T)	111.55 min
Periapsis Altitude (H_p)	252.1262 km
Apoapsis Altitude (H_a)	318.2174 km

2.3. Navigation Requirements

Navigation is expected to meet long-term and short-term prediction requirements in the mission phases. The long-term orbit ephemeris needs to be known well enough to select the observations such that the predicted off-nadir pointing will not exceed more than 3 degrees 28 days from orbit determination data cutoff. The 3-degree uncertainty is equivalent to about 195 km of downtrack error or 59 seconds of timing error at the equator. The short-term prediction needs to satisfy 1.5 km of downtrack accuracy, which is about 0.43 seconds in terms of timing uncertainty. To meet these requirements during science operations, MRO navigation team must account for drag from the highly uncertain atmosphere, which is the dominant error source for ephemeris prediction. To minimize the modeling errors of the non-gravitational forces such as atmospheric drag and solar radiation pressure, Navigation also needs to have the capability to receive, process, and generate the quaternion data and small force files to satisfy the spacecraft dynamic models for orbit determination. Table 2 summarizes the navigation requirements which are provided in the MRO Navigation Plan (Reference 8).

Table 2. Summary of Navigation requirements.

	Position - 3σ		
	Downtrack	Radial	Crosstrack
Short-Term Predict	1.5 km	40 m	50 m
Long-Term Predict	195 km (3°)	—	—
Reconstruction	100 m	1.5 m	40 m

3. Navigation System

3.1. Modeling of Spacecraft Dynamics

Accurate modeling of the forces acting on the spacecraft is important for quality navigation. The major forces are:

1. Martian atmosphere drag;
2. Mars gravity field;
3. Location of the planets and Mars satellites, and their perturbations on the MRO trajectory;
4. Solar radiation pressure, which acts on the irregular-shaped spacecraft bus, and gimbal-enabled solar array and high gain antenna;
5. Thruster firings occurring for the momentum buildup desaturation, attitude control, or any unexpected anomalies;
6. Propulsive maneuvers implemented for trajectory/orbit control;
7. Acceleration resulting from the thermal imbalance; and
8. Any unanticipated outgassing;

Once MRO entered orbit around Mars, the importance of the modeling of thermal imbalance and outgassing was greatly reduced. The accuracy of the solar radiation pressure also became less critical. For most of the mission, the planetary ephemeris DE-410 was used, which was accurate to several hundred meters. As time progressed, the accuracy of this ephemeris decreased, more recent ephemerides became available, and accurate support for Mars landers became more important. MRO transitioned to DE-421 on June 22, 2016.

During the science mission the important forces which had to be modeled were the atmosphere, angular momentum desaturations (AMDs), and Mars gravity field. Mars-GRAM (Mars Global Reference Atmospheric Model)[9] was used to model the atmospheric drag effects. Navigation received thruster firing

information for AMDs from the Spacecraft Team (SCT). The thruster pairs are balanced, and thus should impart no net momentum on the spacecraft. However, in practice, they do impart a small ΔV. The information received from SCT was generally not accurate enough to satisfy the high accuracy requirements levied on the Navigation Team. Thus Navigation estimated the AMD ΔVs and used that data to calibrate the information received from SCT.

The many years that Mars Global Surveyor and Mars Odyssey were in orbit provided extensive data with which to enhance the Mars gravity field. However, both orbiters were at significantly higher altitudes than MRO. The MRO95A Mars gravity field included a year of MRO orbit data, up to September 3, 2007. It has been in use by MRO since late 2007.

To model the spacecraft dynamics and observations, JPL's Double Precision Trajectory (DPTRAJ) and Orbit Determination Program (ODP) were initially used for MRO operations. However, the JPL Mission Design and Navigation section developed a replacement to the Navigation software called MONTE[10] (Mission Analysis, Operations, and Navigation Toolkit Environment). After extensive testing, MRO successfully transitioned to MONTE in March 2010.

3.2. Tracking Data

Two-way X-band Doppler has been the main data type for all mission phases. Furthermore, when in orbit around Mars, Doppler is the only measurement required due to its strong signature from the orbit being tied to the planet. Since MRO has an Ultra Stable Oscillator (USO), one-way X-band Doppler was also available. The one-way Doppler was significantly noisier than the two-way Doppler, and had signatures in the data. However it was still usable as a supplement to two-way Doppler. During solar conjunction the one-way Doppler was especially useful, since the two-way Doppler was either not available or extremely degraded. After several years in orbit, the USO became less stable and the one-way Doppler was no longer of use for Navigation.

When using Earth stations in the processing of tracking data, one must include modeling for polar motion, UT1-TAI timing corrections, solid Earth tides, and Earth center of mass correction. Both seasonal and the diurnal troposphere and ionosphere calibrations are also included in the processing of tracking data. Polar motion and timing corrections are input via the Earth Orientation Parameter (EOP) data file. Continuous DSN tracking was maintained during launch, approach to Mars and aerobraking phases. The tracking was reduced in early PSP; 12 to 16 hours of tracking per day is typical.

The observed tracking data is differenced with the computed values based on the dynamic and observational models described above. A linearized least-squares type of filtering is performed to minimize the resultant residuals by adjusting, or estimating, a subset of the model parameters. The filter also computes error estimates on the updated parameter values. "Stochastic" parameters may be used to model estimated parameters which vary with time via a piece-wise constant algorithm. Additional parameters may be "considered". The errors associated with these parameters are fixed, and the effect of these errors on the rest of the filter is examined. Finally, the estimated parameter values and uncertainties may be mapped to a given time and coordinate system. The behavior of the filter under different scenarios may be investigated by varying the a priori uncertainties of estimated, stochastic and/or considered parameters.

Before orbit operations, the purpose of the filter strategy was to perform covariance analyses to estimate the spacecraft ephemeris accuracies that could be achieved during operations while in orbit around Mars. However, once orbit operations started, the emphasis switched to accurately estimating parameters in an efficient process. It was then important to fit the Doppler data well and verify that the estimated updates to parameters in this orbit determination solution were reasonable. Expected trajectory accuracies had already been calculated before operations. Furthermore, since density was the main error source in the predictions, estimated predicted position accuracies could be quickly calculated with small side tools, if necessary. Thus the operations filter setup was simplified, and all consider parameters removed.

The operations mapping orbit filter strategy was fairly standard for Mars orbiters. Estimated parameters included the state, the density via a scale factor on the Mars-GRAM model, a subset of the gravity field, momentum desaturations, and the solar radiation pressure.

3.2.1. Filter Setup

Table 2 in Reference 2) shows the estimated parameters and their corresponding 1σ a priori uncertainties which were used in the pre-operations covariance analyses. As previously mentioned, the filter setup was simplified for operations, and was fairly standard for operational Mars orbiters. The typical estimated parameters were the state, periapsis densities, momentum desaturations, the Mars gravity, and the solar radiation pressure. The a priori sigmas on the state were loose as in the covariance studies (100 km, 10 m/s). The a priori sigma on the 1.0 solar pressure scale factor was 0.1 (10%) or smaller. Due to the large orbit-to-orbit variability, a separate density was generally estimated for each orbit. This was achieved by treating the density as a stochastic parameter, with a batch size of one orbit, and estimating for a scale factor on the density calculated by Mars-GRAM. The a priori sigma on the density scale factor was 20% of the nominal scale factor.

The AMDs are estimated via a scale factor on the nominal ΔV along each spacecraft axis. This is accomplished by estimating them as stochastic white noise biases, divided into batches based on the momentum wheel being desaturated. When each wheel is desaturated, a different set of balanced thruster pairs are fired.

Even with the improved MRO95A gravity model, some gravity mis-modeling signature was seen in the Doppler residuals. However, only terms in the near-resonant degrees of 12 and/or 13 needed to be estimated to remove the signature. Note that there are 13.2 orbits per sol, so the MRO orbit is near resonant with the degree and order 13. Since all gravity mis-modeling is soaked up into only a few estimated parameters, the a priori is nominally set to 10-40 times the MRO95A formal uncertainties. As time progressed from the end of the MRO data arc fit in MRO95A, the a priori sigmas had to be increased.

Mis-modeled effects from density, gravity and AMDs can be partially soaked into any one of these parameters. Thus it was important to set the relative filter weighting between these mod-

els via the a priori sigmas to minimize the possibility of a mis-modeling in one parameter being soaked up in another parameter estimate. The above a priori sigmas were tuned to reduce such possibilities.

The Doppler is weighted based on its noise over arcs of continuous data. If the infrequent three-way Doppler is available and used, its data weight is further degraded by 20%. The data has more possible error sources due to using two different DSN stations (station clock offsets, etc.). If one-way Doppler is used, its data weight is degraded by at least 50%. The MRO USO frequency reference used by the one-way Doppler is generated by an oven-controlled crystal oscillator with an approximate stability of 10^{-12} over the Doppler count time. Although this stability results in a frequency much less accurate than at the DSN station, it is adequate for Navigation provided one or more sets of frequency bias and rate terms were estimated in a tracking data arc. Except during solar conjunction, Navigation ensured that two-way Doppler surrounded the one-way in order to resolve the bias and rate terms, especially since significant signatures were seen in the one-way data. The one-way Doppler enabled Navigation to fill-in gaps between two-way passes, resulting in drag scale factor estimates on orbits that otherwise would have had no observability.

3.3. Navigation Process

The Navigation Team has two major functional groups: Orbit Determination, and Flight Path/Orbit Control and Trajectory Analysis, sometimes referred to as Maneuver Analysis. Trajectory generation is the fundamental process shared by both groups. Thus special long reference trajectories may be generated by either group, although usually it falls to the maneuver analyst due to maneuvers which need to be included. Trending of trajectory behavior, navigation performance, parameter estimates, and real-time spacecraft event monitoring are related work performed by the Navigation Team.

The files which are regularly delivered and used by Navigation include: spacecraft attitude, small forces (AMDs), tracking data, earth orientation and Earth atmospheric media calibrations. In order to satisfy project requirements, Navigation delivers products twice a week for predicted trajectories and once a week for reconstructed trajectories. The Navigation delivery kicks off the work by the rest of the MRO teams, such as science planning and sequence development. The SPK file is the main Navigation deliverable. It contains the spacecraft ephemeris, converted from the Navigation internal format to the SPK format via NAIF[11] tools. The other Navigation products are derived from the spacecraft ephemeris. The OPTG contains information at discrete orbit events (e.g. periapsis). The light-time file contains information on the topocentric light-time between MRO and the DSN stations. It is used by SCT to update the spacecraft clock file, which defines the time conversion between UTC and the spacecraft clock. The Maneuver Performance File is the Navigation interface to SCT for delivering information on maneuvers that will be executed.

3.3.1. Orbit Determination Process

In operations, project deliveries, data trending, maneuver analyses and reference trajectories are all based on Orbit Determination analyses. As shown in Figure 2, it starts with a full range of information (data and models) collection. Real-
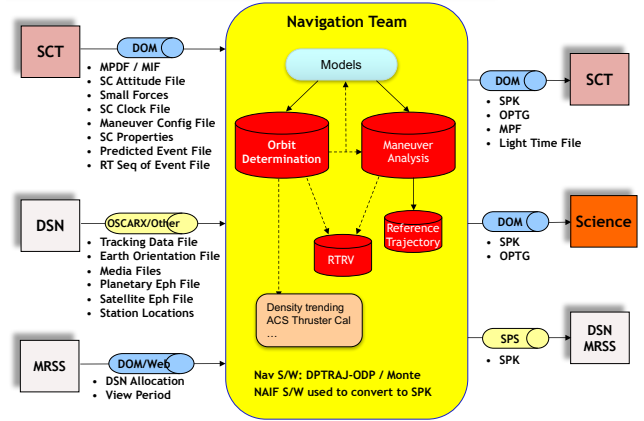

Fig. 2. Simplified navigation process.

time engineering data including reconstructed spacecraft attitude and on-board small forces due to momentum desaturation are generated through the telemetry query system. Along with the tracking data and other ancillary information provided by the Ground Data System, the orbit determination process is performed through detailed modeling and the spacecraft dynamic model fine-tuning, data arc and ancillary data setup, and estimation strategy update.

The DSN schedule determines the availability of MRO Doppler, which determines the time span for the OD analysis. After the most up to date information on models and calibrations have been retrieved, as shown in Figure 2, an orbit solution may be generated via a trajectory integration and filter run. Due to the non-linearity of models, this orbit solution must be iterated to convergence by folding in the updated parameter estimates from one solution into the nominal models of the next solution. The converged OD solution can be integrated out to a later date for covariance analysis, maneuver analysis, and trajectory products generation. The trajectory products are delivered to the project to initiate sequence development, science planning, etc.

The results of the OD solutions may also be used for tracking data and model analyses. The history of model parameter estimates may be trended, and if necessary, used for new calibrations of models. The most obvious example is the density. The current OD solution density estimates, along with the previous history, is used to derive the appropriate scale factor to be applied to the Mars-GRAM density when the trajectory is integrated out for a predict delivery. The past long-term estimated density history may also be examined to get insight into the behavior of the atmosphere model. Figure 3 shows the 39-orbit and 211-orbit running mean of the reconstructed Mars-GRAM density scale factor for matching the actual density variations with predictions.

Another important example are the AMDs. Unfortunately, the thruster calibration performed in cruise did not appear to give good results after Mars orbit insertion. So Navigation needed to find some way to resolve this problem. A scale factor is estimated for each set of thruster pairs in an OD solution. By combining the information from many analyses, the performance of thruster pairs can be resolved and analyzed to produce a pseudo ACS thruster calibration. Even though this greatly enhanced the desaturation calibration in the science phase, there were limitations to this approach, and calibrations did not nec-
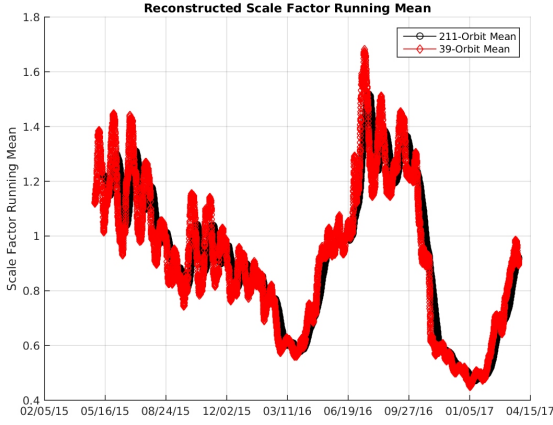
Fig. 3.   Scale factor running mean.

essarily carry over well if quite different desaturation behavior started to occur. So a 100% a priori sigma was still used for the desaturated estimates.

3.3.2.   Maneuver Design Process

The Flight Path/Orbit Control, or Maneuver, analyst is responsible for designing trajectories such that the spacecraft achieves the desired future orbit characteristics. Some examples include controlling the spacecraft ground track walk, controlling the orbit local mean solar time (LMST), and supporting a Mars lander's EDL sequence. The main support the maneuver analyst provides is the design leading to the execution of upcoming OTM's, and the generation of reference trajectories for long-term project planning. The final design, implementation, verification, and execution of an OTM takes 7-10 calendar days for the MRO project.

3.3.3.   Real-Time Residual Viewer

Although not necessary for any project products, the Real-Time Residual Viewer, or RTRV, can be useful for real-time event monitoring, such as a maneuver. For major maneuvers such as MOI or large orbit (inclination) change maneuvers, the project is very interested in getting status information on the maneuver as soon as possible. RTRV shows the Doppler residuals, which shows the projected line-of-sight velocity differences, thereby giving immediate information on the deviation of the actual trajectory from the designed maneuver trajectory.

RTRV can also be used to observe the accuracy of a delivered predicted trajectory. This can be used to post-validate a Navigation delivery, since an error in the predict would cause the Doppler residuals to grow quickly. It can also be used to observe the accuracy of the prediction, since the density behavior relative to the expected (modeled future) behavior is the major perturber of the Doppler residuals.

In addition, Navigation performs real-time archiving of data from the same DSN feed that RTRV uses. This allows Navigation to use the latest Doppler data in predict analyses, which can be useful in meeting the tight short-term predict accuracy requirements.

3.3.4.   Automation of Processes

Since May 2014, MRO has been automating the daily quick-look OD solutions via JPL's automation framework tool called TARDIS[12] (Traceable Automation with Remote Display and Interruptible Scheduler). This paved the way for the Soil Moisture Active Passive (SMAP) mission to utilize TARDIS for their automated predict process. The MRO Navigation Team started

automating the reconstructions of the MRO trajectories in May 2015, marking the first time TARDIS was used by a JPL mission in operations.

4.   Navigation Operations and Performance

4.1.   Orbit Prediction

Navigation operations include predicting the MRO trajectory for long and short terms. The long term prediction typically spans at least 28 days from the time of the OD data cutoff. The requirements for the long and short term predictions are given in Table 2. During the PSP mission the Navigation Team would deliver the trajectory products at least 3 times a week. This was reduced to two times per week beginning with the ESP mission. Even with this relaxed delivery schedule, the requirements are still being met. The longest stretch between predicted trajectories is usually about 5 days prior to an onboard ephemeris update (during PSP the longest stretch was about 4 days due to more frequent updates). Figure 4 shows the prediction errors for all predicted trajectories at the end of 5 days. The dashed blue lines indicate the timing requirement of 0.43 seconds for short term predictions. Occasional outliers happened due to atmospheric density variability especially during high density seasons (around a solar longitude (L_s) of 270°) or safe modes. As can be seen in Figure 4 the larger errors are generally in the third part of each Mars year, especially around the Southern Summer Solstice ($L_s = 270°$). This behavior is evident also in Figure 5 which displays the long term timing errors.
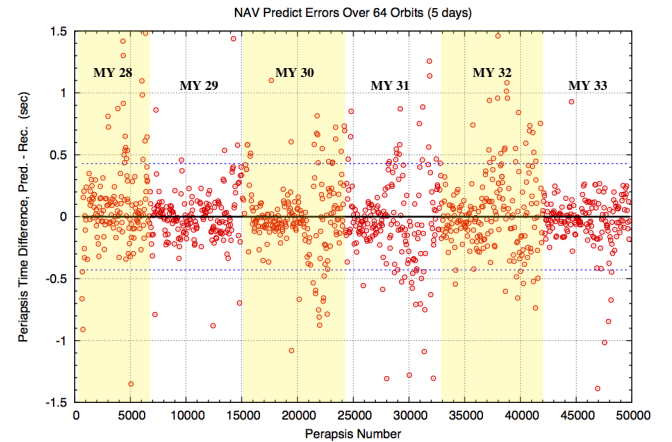

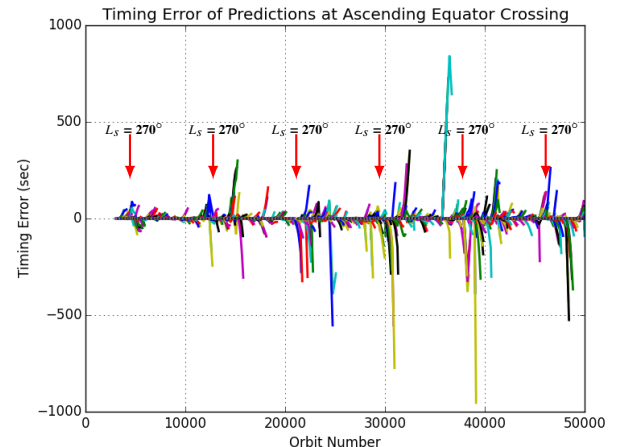Fig. 4.   Short-term predict timing errors vs. orbit over 64 orbits (5 days).

Fig. 5.   Long-term predict timing errors vs. orbit since March 2007.

4.2. Orbit Reconstruction

Reconstruction of MRO's orbit is routinely performed to aid in science data analysis. For example, Figures 6 and 7 provide the reconstructed apoapsis and periapsis altitudes, respectively, since the 252 km × 317 km science orbit was established in November 2006. It can be seen that both apoapsis and periapsis have been maintained within ±5 km of the nominal values. Reconstruction batches spanning about 1.5 days are processed daily and overlapping trajectories compared to ensure that the requirements are satisfied. Figures 8, 9, and 10 indicate typical comparisons in the radial, tangential, and normal directions. Occasional violations were limited to singularities in the Earth beta angles or during safe modes. At times of high Earth beta angle (e.g., near a singularity of 90 deg), when the orbit plane is almost perpendicular to the Earth line of sight, the spacecraft position in the radial and tangential directions were poorly determined (see Figures 8 and 9). Similarly, the position in the normal direction was poorly determined when the Earth beta angle crossed zero 4 times (see Figure 11) in the early years of the mission. Since the dramatic increase in one-way Doppler data noise (a two-orders of magnitude jump since January 2012) only two-way and three-way Doppler data are currently used for reconstructions. Reconstructions during solar conjunctions were done by anchoring a longer than usual time span of one-way Doppler data with two-way data on both sides. Since May 2015 the Navigation Team has been performing the routine reconstructions via an automated process and only intervened manually as needed.
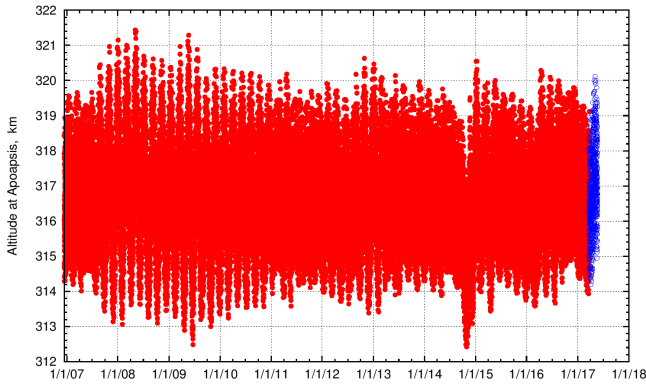

Fig. 6.   Reconstructed apoapsis altitude (November 2006 – March 2017).
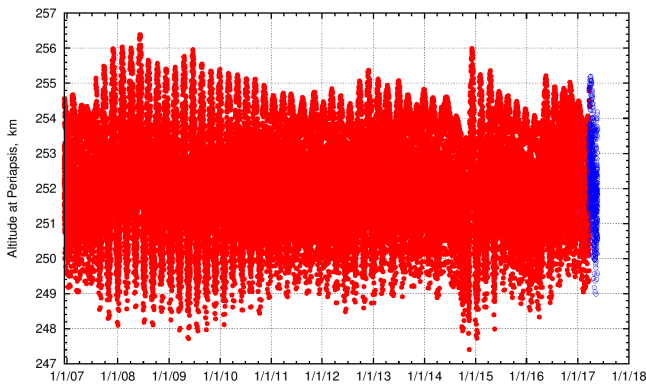

Fig. 7.   Reconstructed periapsis altitude (November 2006 – March 2017).
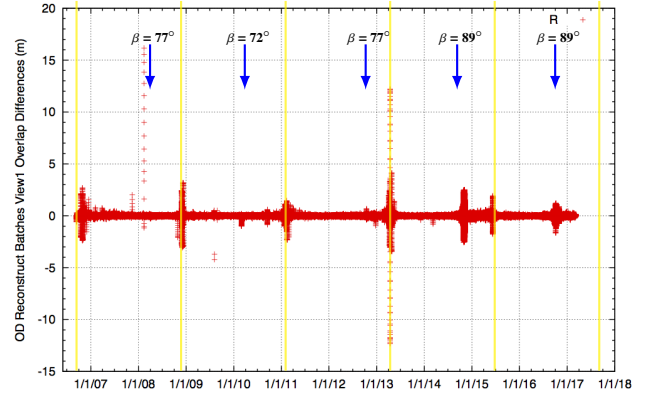

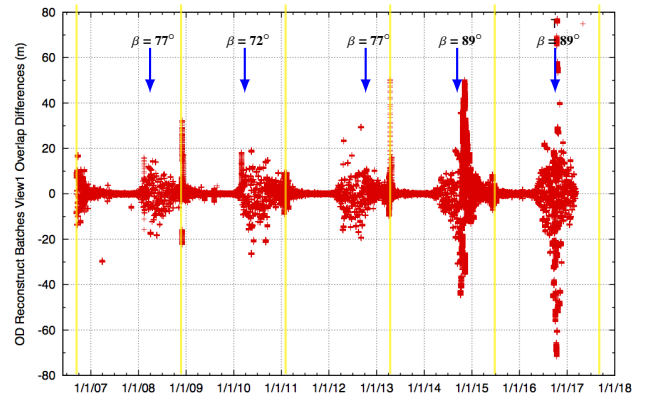Fig. 8.   OD reconstructed batches View1 overlap differences – radial.

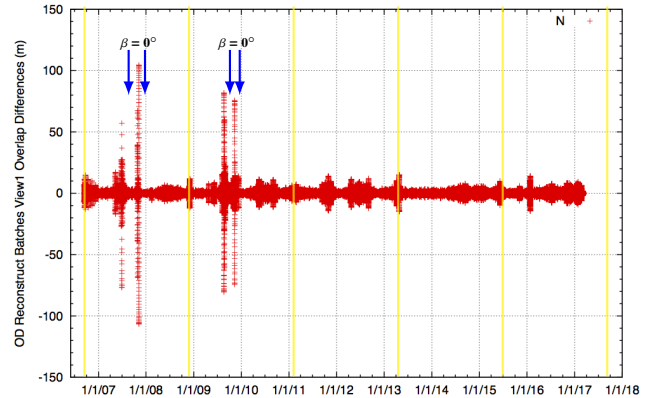Fig. 9.   OD reconstructed batches View1 overlap differences – tangential.

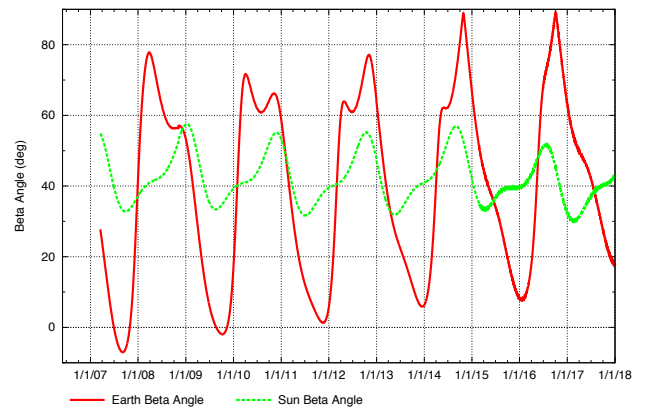Fig. 10.   OD reconstructed batches View1 overlap differences – normal.

Fig. 11.   MRO Earth and Sun beta angles (2007–2018).

4.3. Maneuvers

MRO Navigation has performed OTMs in typically one of two standard maneuver orientations, or a hybrid of the two: in-plane (parallel to the spacecraft velocity vector) or out-of-plane (along the spacecraft angular momentum vector). The burns are executed as fixed-attitude maneuvers and are usually scheduled for the first Wednesday morning of a new two-week spacecraft background sequence starting on Sunday. The maneuvers performed since science operations began in November 2006 are summarized in Table 3. For each maneuver, the table lists the burn time, burn location in the orbit (apsis or equator crossing), and the reconstructed maneuver ΔV magnitude. Maneuvers are also grouped according to mission phase as indicated in the table. Depending on the maneuver size, the Spacecraft Team at Lockheed Martin used either a 25% or 75% duty cycle for MRO burns, the latter of which was utilized for all inclination-change maneuvers performed (OTMs 12, 39, 43, 44, and 48). Also, the minimum maneuver capability of 20 mm/s in ΔV magnitude was considered when designing these maneuvers. Reference 3) provides further details on these maneuvers, including an assessment of the maneuver performance.

Table 3. MRO maneuver history (February 2007 – March 2017). *Note: Inclination-change maneuvers are indicated in bold.*

Orbit Trim Maneuver (OTM)		Apsis or Node	ΔV Mag. (m/s)	Orbit Trim Maneuver (OTM)		Apsis or Node	ΔV Mag. (m/s)
#	Date			#	Date		
PSP — 01-Jan-2007 to 31-Dec-2008				24	20-Jul-2011	Peri	0.2666
01	07-Feb-2007	Apo	0.0711	25	12-Oct-2011	Peri	0.2923
02	18-Apr-2007	Peri	0.1302	26	01-Feb-2012	Peri	0.1521
03	23-May-2007	Apo	0.1128	27	13-Jul-2012	Peri	0.1305
04	27-Jun-2007	Peri	0.1230	28	29-Aug-2012	Peri	0.2591
05	25-Jul-2007	Apo	0.2248	**EM2 — 01-Oct-2012 to 30-Sep-2014**			
06	22-Aug-2007	Peri	0.1416	29	24-Oct-2012	Peri	0.1830
07	19-Sep-2007	Apo	0.0816	30	19-Dec-2012	Apo	0.2953
08	31-Oct-2007	Peri	0.1925	31	13-Feb-2013	Peri	0.2957
09	12-Dec-2007	Apo	0.0764	32	27-Mar-2013	Peri	0.2834
OSM-1	06-Feb-2008	Peri	0.1520	33	05-Jun-2013	Peri	0.4011
OSM-2	30-Apr-2008	Peri	0.1223	34	31-Jul-2013	Apo	0.1990
10	25-Jun-2008	~Apo	0.2485	35	20-Nov-2013	Peri	0.2411
11	15-Oct-2008	Peri	0.1078	36	07-May-2014	Peri	0.3092
ESP — 01-Jan-2009 to 30-Sep-2010				37	02-Jul-2014	Peri	0.0649
12	**04-Feb-2009**	**DEq**	**3.1943**	38	25-Sep-2014	Apo	0.2773
13	18-Mar-2009	Peri	0.1525	**EM3 — 01-Oct-2014 to 30-Sep-2016**			
14	13-May-2009	Peri	0.1627	**39**	**19-Nov-2014**	**DEq**	**3.4597**
15	24-Jun-2009	Peri	0.1589	40	28-Jan-2015	AEq	0.4342
16	19-Aug-2009	Peri	0.1315	41	25-Mar-2015	Peri	0.3239
17	03-Mar-2010	Peri	0.1235	42	20-May-2015	Apo	0.3530
18	21-Jul-2010	Peri	0.0940	**43**	**29-Jul-2015**	**DEq**	**5.3401**
EM1 — 01-Oct-2010 to 30-Sep-2012				**44**	**06-Apr-2016**	**AEq**	**7.9166**
19	10-Nov-2010	Peri	0.1543	45	27-Jul-2016	Peri	0.1921
20	13-Jan-2011	Peri	0.1603	46	14-Sep-2016	Peri	0.2102
21	02-Mar-2011	Peri	0.2160	**EM4 — 01-Oct-2016 to 30-Sep-2018**			
22	13-Apr-2011	Peri	0.2745	47	02-Nov-2016	Apo	0.2241
23	25-May-2011	Peri	0.2364	**48**	**22-Mar-2017**	**DEq**	**3.2032**

4.4. GTW Error Maintenance

Figures 12 and 13 show the reconstructed ground track walk (GTW) repeat error from January 1, 2007 to April 9, 2017, covering 50 maneuvers performed since science operations began in November 2006. During PSP, pro-velocity in-plane maneuvers were used for apsis height control to maintain the PSO GTW repeat error between ±10 km with OTMs 1–10 (Figure 12). This GTW error control band was relaxed to ±20 km

during ESP with OTMs 11–19, ±30 km in the first half of EM1 with OTMs 20–23, and ±40 km in the second half of EM1 through EM3 with OTMs 24–47. Beginning with OTM-48 (OCM-3) in March 2017, the GTW error control band was loosened to ±60 km. Of note in Figure 12 are the GTW error effects of the safe mode and AMD ΔVs that occurred between October 2009 and April 2010.
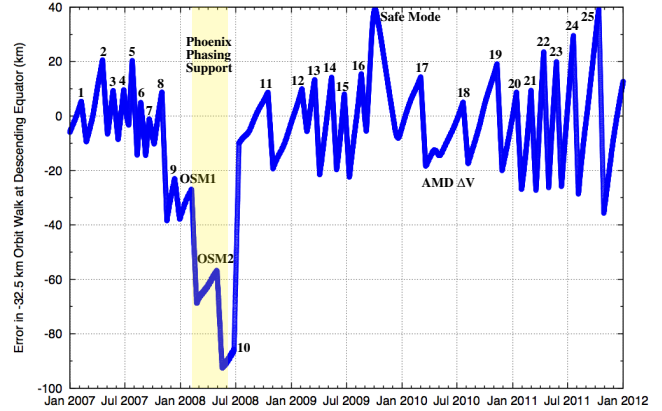

Fig. 12. Reconstructed GTW repeat error from January 1, 2007 – January 1, 2012 (OTMs 1–25).
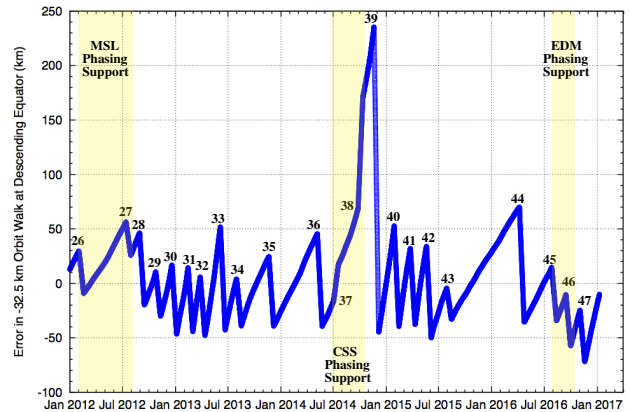

Fig. 13. Reconstructed GTW repeat error from January 1, 2012 – April 9, 2017 (OTMs 26–48).

During the Comet Siding Spring (CSS) risk mitigation period, two anti-velocity maneuvers were performed which resulted in an unprecedented GTW error of almost +240 km, as seen in Fig. 12.[5] In comparison, the GTW errors reached about −90 km during the Phoenix EDL support period (Fig. 12),[2] about +55 km during the MSL EDL coverage (Fig. 13),[4] and nearly −60 km during the Schiaparelli overflight support period (Fig. 13).[6]

4.5. Frozen Condition Maintenance

MRO Navigation is required to keep the orbit frozen, but there is no specific requirement for how the e-w curve should be. The MRO Navigation Team currently contains the e-ω variation such that ω varies within 3 deg about 270 deg. For comparison, Mars Global Surveyor had kept e-ω between 263° and 277° (at apoapsis); Mars Odyssey has been within 262° and 278° (at apoapsis). The entire mean e-ω reconstructed history from the beginning of science operations in November 2006 through

just prior to the execution of the most recent maneuver performed in March 2017 (OTM-48) is shown in Figure 14. Reference 3) provides more detail on the effects of each maneuver on the frozen condition.
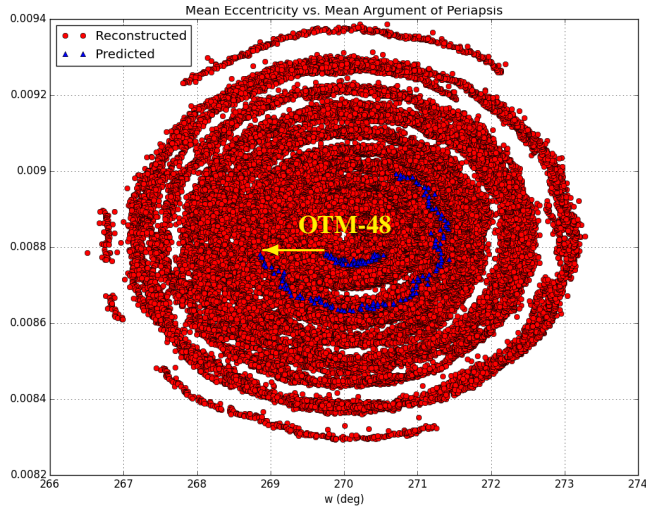

Fig. 14. Reconstructed mean $e - w$ (frozen about Mars South pole) from January 2007 – March 2017.

4.6. Orbit Phasing

Orbit phasing is accomplished through in-plane Orbit Synchronization Maneuvers (OSMs). An OSM is used to adjust the MRO orbital period and, over a given duration, produce a desired total MRO orbit down-track timing change. Table 4 presents a summary of the phasing offsets that MRO achieved in support of the EDL sequences of Phoenix and MSL in May 2008 and August 2012, respectively, the protected location from the CSS incoming particles in October 2014, and the third overflight of the Schiaparelli landing site in October 2016. As can be seen in the table, the final phasing offsets from the requested target times were well within the phasing requirements. Note that OSMs are OTMs used for phasing and the OSM numbers are reset with each phasing target; the OSM-1 and OSM-2 used for Phoenix phasing were the actual maneuver names.

Table 4. Orbit phasing maneuver history.

Phasing Target	Phoenix EDL	MSL EDL	CSS Flyby Safe Location	Schiaparelli 3rd Overflight
2000 IAU Mars Fixed Target Time (SCET)	25-May-2008 23:32:07.0026 ET	06-Aug-2012 05:11:54.5626 ET	19-Oct-2014 20:07:00 UTC	20-Oct-2016 17:17:43.7890 ET
Target Latitude	48.0311 deg	−26.5011 deg	7.6042 deg	−2.05 deg
Pre-OSM Offset	**23.7 min early**	**48.9 min early**	**19.0 min late**	**30.6 min early**
OSM Location	OSM-1	OTM-26 (OSM-1)	OTM-37 (OSM-1)	OTM-45 (OSM-1)
OSM Correction	**20.7 min early**	**36.5 min early**	**9.0 min late**	**20.6 min early**
Post-OSM Offset	2.6 min early	12.4 min early	6.1 min late	9.5 min early
OSM Location	OSM-2	OTM-27 (OSM-3)	OTM-38 (OSM-2)	OTM-46 (OSM-2)
OSM Correction	**3.9 min early**	**3.8 min early**	**8.4 min late**	**9.6 min early**
Post-OSM Offset	2.5 min early	11.3 sec late	23.7 sec early	2.5 min late
Requirement	**±30 sec**	**±30 sec**	**±2 min**	**±5 min**
Final Phasing Offset	**0.25 sec early**	**9.0 sec late**	**57.0 sec early**	**10.4 sec late**
Comments	Low density. OTMs 08 & 09 used to reduce ~45 min phasing offset.	Low density. Cancelled OSM-2 on 20-Jun-2012.	High density. Phasing target was arrival time of peak particle fluency.	High density. Phasing target was maximum elevation time at third overflight.
Reference	Highsmith (Reference 2)	Williams (Reference 4)	Menon (Reference 5)	Menon (Reference 6)

4.7. LMST Control

Out-of-plane maneuvers are implemented to control the LMST drift by changing the inclination. These maneuvers have been used to return MRO to the PSO operating bounds (3:00 PM ± 15 minutes LMST). Inclination-change maneuvers used for EDL support are referred to as Orbit Change Maneuvers (OCMs). Figure 15 shows the reconstructed LMST profile from January 2007 through March 2017 (in red), as well as the maneuvers that were performed to control the LMST drift.
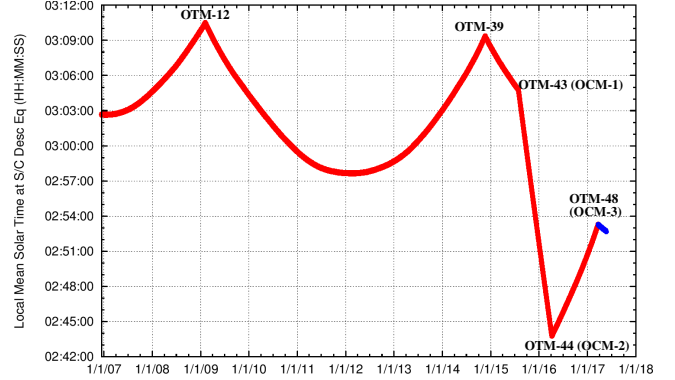

Fig. 15. Reconstructed LMST from January 2007 – March 2017. *Reconstructed (red), predicted (blue).*

Inclination-change maneuvers have been implemented three times in the mission to drift the LMST back towards 3:00 PM at the ascending equator crossing: OTM-12 in February 2009, OTM-39 in November 2014, and OTM-44 in April 2016. The spacecraft is required to operate within a Local True Solar Time (LTST) range of 2 PM to 4 PM. Hence, the orbit plane change maneuvers were designed complying with this limitation. Three OCMs have been implemented in relation to InSight EDL support. OTM-43 (OCM-1) was performed on July 29, 2015 at the descending equator to change the nodal drift such that 2:30 PM LMST would be achieved on September 28, 2016, the original date for InSight EDL. After the postponement of the InSight launch, OTM-44 (OCM-2) on April 6, 2016 was performed at the ascending equator to re-establish the 3:00 PM LMST PSO configuration. OTM-48 (OCM-3) was performed on March 22, 2017 to arrest the LMST drift such that the 2:52 PM LMST requirement will be met by the InSight EDL timeframe on November 26, 2018. Table 5 summarizes the three OCMs performed thus far for InSight EDL support. The OCM strategies for InSight EDL support are described in Reference 7.

Table 5. OCMs for InSight EDL support.

Maneuver	Maneuver Epoch (UTC-SCET)	ΔV (m/s)	Comments
OCM-1 (OTM-43)	29-Jul-2015 13:21:31	5.34	2:30 PM LMST for InSight EDL in 2016
OCM-2 (OTM-44)	06-Apr-2016 13:31:09	7.92	Return to 3 PM LMST for MRO PSO
OCM-3 (OTM-48)	22-Mar-2017 13:38:40	3.20	2:52 PM LMST for InSight EDL in 2018
	Total	**16.46**	

5. MRO Propellant Consumption

Figure 16 shows the propellant consumed by momentum desaturations, maneuvers, and safe mode events on an annual basis. The annual budget for propellant usage is 15.4 kg: 13 kg for desats and 2.4 kg for maneuvers. The large amount of propellant used by the five inclination-change maneuvers performed thus far are reflected in the calendar year 2009, fiscal year 2015, and fiscal year 2016 budgets (in red). Also of note is the substantial amount of propellant used for safe modes in calendar year 2009 (in yellow).
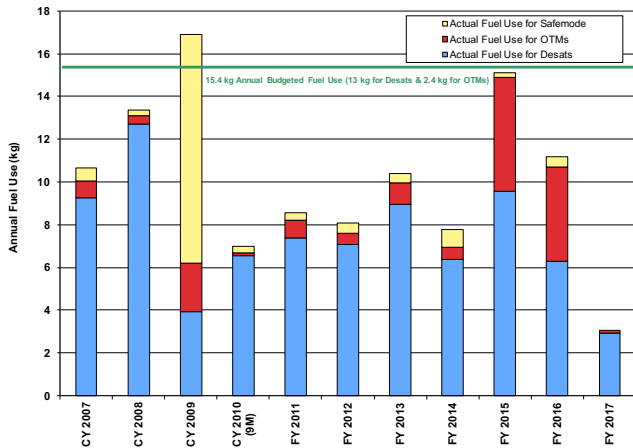
Fig. 16.   MRO annual propellant usage (January 2007 – March 2017).

6. Navigation Challenges

The MRO Navigation Team occasionally deals with various challenges outside of nominal operations. These include solar conjunction, seasonal dust activity, and potential close approach concerns with other Martian orbiters. When the Sun-Earth-Probe (SEP) angle is below 2 degrees due to solar conjunction, only very noisy 1-Way Doppler data is available. Hence, the predicted trajectory using 2-Way Doppler data generated before this time period is used for operations. Reconstruction of the trajectory is done by anchoring the two ends of a very long 1-Way Doppler data arc with 2-Way Doppler data. Critical activities such as maneuvers are also avoided during the solar conjunction period.

Mars missions have seen increased dust activity when the solar longitude (L_s) is between 180 and 360 degrees. The scientific results have concluded that there are generally three distinct dust activities (A, B, and C) in the southern region during this period. The drag ΔV profiles during the past six high density seasons are shown in Figure 17. The three dust storms in 2014 are quite visible. Occasionally the dust activity could bloom into a global dust storm like in 2007. Navigation operations could see elevated atmospheric density scale factor (DSF) during these times.

Due to the increasingly crowded Martian environment potential collision with other orbiters is an ongoing concern. This has resulted in increased vigilance and an automated process is in place to assess any potential close approaches by other spacecraft to MRO. A process to take mitigative action if needed also exists.
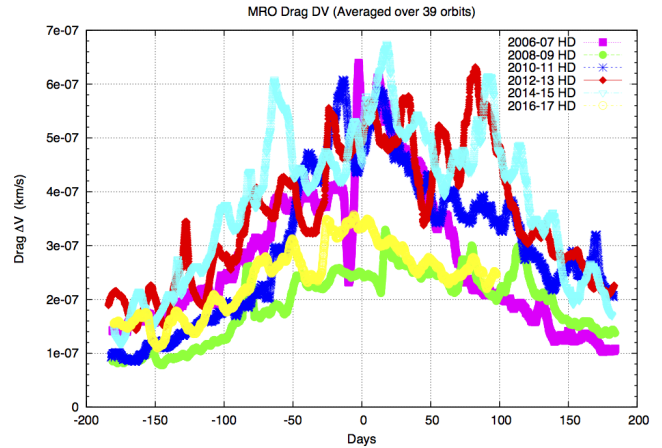

Fig. 17.   MRO drag ΔV per orbit. *Days from Southern Summer Solstice (Day 0: $L_s = 270°$).*

7. Extended Mission Highlights

7.1. Mars Science Laboratory – August 2012

Like the earlier support for the Phoenix lander in 2008, MRO successfully provided relay support using its UHF antenna during the Mars Science Laboratory's EDL phase on August 6, 2012. This success required accurate phasing of MRO to the MSL relay target via the execution of two propulsive maneuvers designed by the MRO Navigation Team.[4] MRO's HiRISE camera also took a picture of the parachute landing of MSL (Figure 18).
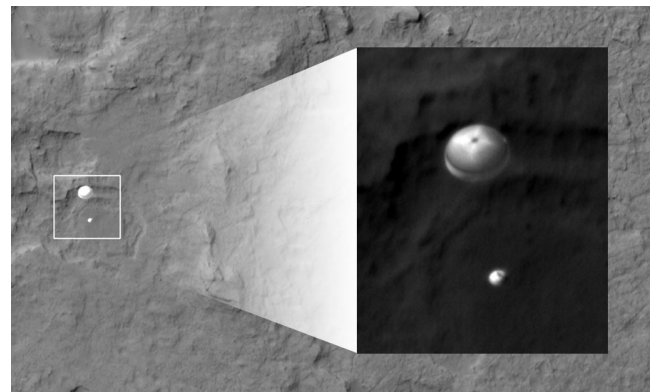

Fig. 18.   Image of MSL parachute landing taken by HiRISE Camera.

7.2. Comet Siding Spring Flyby – October 2014

Comet Siding Spring encountered Mars on October 19, 2014 at a distance of about 140,500 km — the nearest comet flyby of a planet in recorded history. MRO was able to detect the comet, gather science data, and capture images of the comet as it approached Mars. To help protect MRO from the incoming comet particles, the Navigation Team designed two propulsive maneuvers to position the spacecraft behind Mars at the arrival time of the expected peak particle fluency. The MRO Navigation Team also provided viewing periods with and without atmospheric occultation effects to aid the observations of the comet.[5] The scientific findings by MRO resulted in the improved knowledge of the comet's rotation period (eight hours). The images obtained was able to resolve the lit part of the comet nucleus as shown in Figure 19. The morphology and composition of the coma were also better understood. Four jets were detected on

the comet of which three were on the Sun-side at the time of the observation.
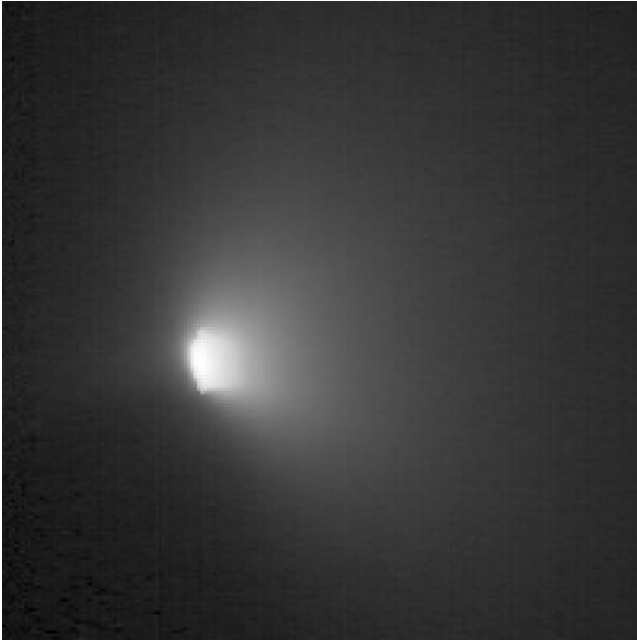

Fig. 19. Closest approach image of Comet Siding Spring taken by HiRISE Camera (nucleus saturated). *18:24 UTC at a range of 139,000 km, 28×28 km field-of-view. Source: Alan Delamere.*

7.3. ExoMars Schiaparelli Lander – October 2016

MRO planned to provide surface relay support for the brief mission of the ExoMars Schiaparelli EDM lander on Mars in October 2016. To place MRO directly overhead on its third overflight of the Schiaparelli landing site, two propulsive maneuvers designed by the MRO Navigation Team were performed starting three months prior to Schiaparelli's arrival at Mars. This strategy allowed MRO to perform its overflight within about 10 seconds of the targeted time.[6] However, the plan to provide relay support for Schiaparelli was repurposed into acquiring pictures of the impact site after an unsuccessful landing.

MRO's Context Camera (CTX) was used to look for evidence of the landed parts a day after Schiaparelli's arrival at Mars. Based on the information obtained by CTX, the High Resolution Imaging Science Experiment (HiRISE) camera was used to take images that revealed three separate locations showing the lander, the parachute, and the heat shield. The HiRISE picture taken on November 1, 2016 during the third overflight observations period details what is believed to be the main spacecraft's impact location, the lower heat shield, and upper heat shield and parachute (Figure 20). With this image, some of the bright spots around the impact area were confirmed to be from material from Schiaparelli.

7.4. Lunar Calibration – November 2016

MRO was about 205 million km away when it took pictures of both the Earth and Moon on November 20, 2016. Figure 21 shows a composite of both images, where Australia and Southeast Asia are the reddish areas in the middle and near the top of the Earth, respectively, and Antarctica is the bright spot on the bottom left. The well-exposed side of the Moon will be used to provide absolute radiometric calibration for MRO.
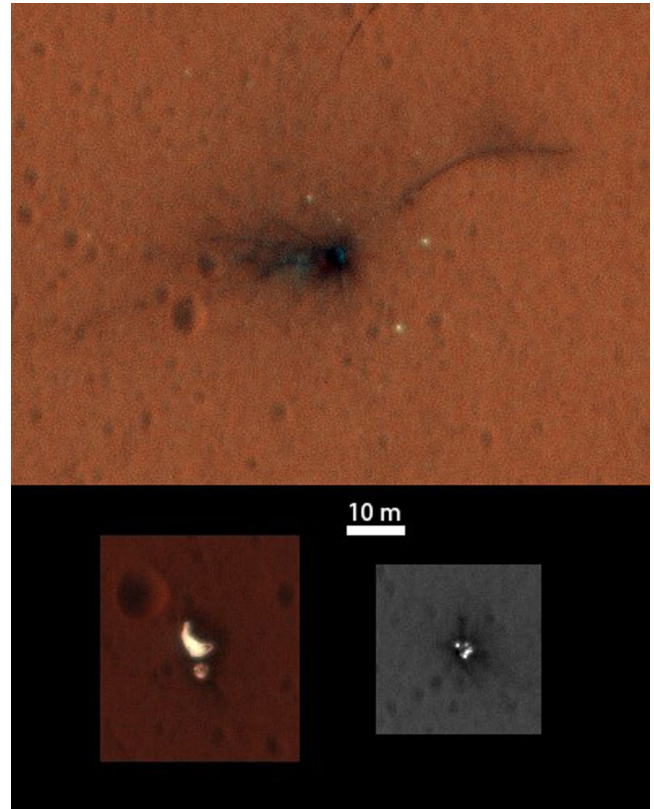

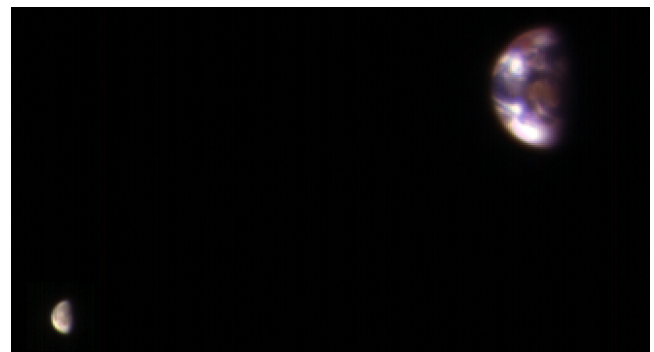Fig. 20. Image of the Schiaparelli impact area taken by HiRISE on November 1, 2016. Source: NASA/JPL-Caltech.

Fig. 21. Lunar calibration images of Earth and Moon taken by HiRISE Camera (IRB color). Source: NASA/JPL-Caltech.

8. Conclusion

The MRO Navigation Team has successfully supported science operations and relay for landed missions at Mars for over 10 years. Navigation requirements have been consistently met through periodic trajectory prediction and reconstruction deliveries. Fifty propulsive maneuvers performed since February 2007 were successful in controlling the GTW errors within mission requirements while maintaining the frozen condition of the science orbit. MRO also implemented maneuvers that satisfied LMST requirements for the PSO and the upcoming InSight mission. As of February 2017, MRO has a generous margin of about 209 kg of usable propellant, which translates to nearly 400 m/s of remaining ΔV. MRO will continue its science endeavors and relay support of landed assets at Mars, as well as provide relay support for future missions such as InSight and Mars 2020.

Acknowledgments

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